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Correlations in the associative production of B_c and D mesons at LHC

Aleksander Berezhnoy[*†]
SINP MSU, Moscow, Russia
E-mail: aber@trtk.ru

Anatolii Likhoded
IHEP, Provtino, Russia
E-mail: Anatolii.Likhoded@ihep.ru

It is shown that the study of correlations in the associative production of B_c and $\bar{D}$ mesons at LHC allows to obtain the essential information about the B_c production mechanism.

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*Speaker.

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1. Introduction

Recent measurements of B_c meson mass and lifetime in CDF [1] and D0 [2] experiments are the first steps in the experimental research of quarkonia with open flavor. The measurement results are in a good agreement with the theoretical predictions for the B_c mass [3, 4, 5]:

$$m_{B_c}^{\rm CDF} = 6.2756 \pm 0.0029(\text{stat.}) \pm 0.0025(\text{sys.})\ \text{GeV},$$

$$m_{B_c}^{\rm D0} = 6.3000 \pm 0.0014(\text{stat.}) \pm 0.0005(\text{sys.})\ \text{GeV},$$

$$m_{B_c}^{\rm theor} = 6.25 \pm 0.03\ \text{GeV};$$

as well as for the decay time [6, 7]:

$$\tau_{B_c}^{\rm CDF} = 0.448^{+0.038}_{-0.036}(\text{stat.}) \pm 0.032(\text{sys.})\ \text{ps},$$

$$\tau_{B_c}^{\rm D0} = 0.475^{+0.053}_{-0.049}(\text{stat.}) \pm 0.018(\text{sys.})\ \text{ps},$$

$$\tau_{B_c}^{\rm theor} = 0.48 \pm 0.05\ \text{ps}.$$

Unfortunately, the experimental estimations of the cross section value were not published. Thus, the mechanism of B_c meson production can not be understood from the obtained data due to poor experimental statistics, as well as due to large uncertainties in the theoretical predictions. Only the planed experimental research at LHC, where about 10^{10} events with B_c mesons per year are expected, will improve the situation. This huge amount of events will allow to obtain the information on the production cross section distributions, on the decay branching fractions, and in some cases, on the distributions of decay products. In this research we try to fill the gap in our theoretical understanding of B_c production and show that the study of correlations in the associative production of B_c and $\bar{D}$ meson at LHC could be an essential information source of B_c production mechanism. Here we study the production characteristics which weakly depend on parameters: the cross section distribution shapes and the ratio between B_c^* and B_c yields.

2. Fragmentation and recombination contributions into B_c production

The B_c production amplitude within the discussed approach can be subdivided into two parts: the hard production of two heavy quark pairs calculated in the framework of perturbative QCD and the soft nonperturbative binding of $\bar{b}$ and c quarks into quarkonium described by nonrelativistic wave function. The calculations within the discussed technique are the most simple for the process of B_c production in the e^+e^- annihilation. As it was shown in [8, 9, 10], the special choice of the gluonic field gauge allows to interpret the B_c production process as the $\bar{b}$ quark production followed by the fragmentation of $\bar{b}$ quark into B_c meson. Thus, in the e^+e^- annihilation at large energies the consideration of leading diagrams for the B_c meson production leads the well known factorized formula for the cross section distribution over $z = 2E_{B_c}/\sqrt{s}$:

$$\frac{d\sigma}{dz} = \sigma_{b\bar{b}} \cdot D(z). \tag{2.1}$$

The analytical forms of fragmentation functions for S wave states are known from [8, 9].

The relative yield of B_c^* and B_c in the e^+e^- annihilation obtained within pQCD calculation $R^{B_c}_{e^+e^-} = \sigma(B_c^*)/\sigma(B_c) \sim 1.4$. Thus the naive spin counting which fairly predicts this ratio for B^* and B ($R^{B}_{e^+e^-} \sim 3$) can not be applied to B_c and B_c production.

At first sight it would be reasonable to assume that for the gluonic B_c production the fragmentation mechanism is also dominant at least from transverse momenta larger than B_c mass. But as it was shown in [11, 12, 10, 13] the other mechanism essentially contribute to this process practically all over the phase space and the fragmentation approach is valid only at transverse momenta larger than $5 \div 6$ masses of B_c. The total gluonic cross section predicted using full set of leading order diagrams essentially differ from the fragmentation approach in absolute value as well as in shape of interaction energy dependence.

As it is predicted within pQCD [11, 12], about 90 % of the B_c mesons at LHC energies will be produced in the gluonic fusion (Fig. 1). Therefore in our pQCD calculations we can neglect the other partonic subprocess. The convolution of the gluonic subprocess cross section with the gluonic structure functions partially hides the differences between the pQCD predictions and the fragmentation approach. The predicted ratio between the hadronic cross section values is about of 2. Obviously, such a difference is not essential for the calculations of forth order on α_s. Nevertheless, the relative yield of B_c^* and B_c does not depend on α_s and could indicate the production mechanism. Even in the kinematical region where the fragmentation model could be applied the value of $R_{\text{hadr}} = \sigma_{\text{hadr}}(B_c^*)/\sigma_{\text{hadr}}(B_c)$ predicted within pQCD is about 2.6 instead of 1.4 obtained within the fragmentation approach. To measure this value one need to detect B_c^* meson which with unit probability decays into B_c and photon. However, it is quite difficult to detect such a process experimentally due to the small mass difference between B_c^* and B_c mesons [3]: $\Delta M = M_{B_c^*} - M_{B_c} = 65 \pm 15$ MeV. In laboratory system the maximum energy of emitted photon is $\omega_{max} = \left(\gamma + \sqrt{(\gamma^2-1)}\right)\Delta M$, where γ is B_c^* γ factor, and even for B_c^* with energy ~ 30 GeV $\omega_{max} \sim 0.7$ GeV. Thus one can conclude that there is no certainty that the method based on separation of B_c^* from B_c can be used to study the B_c production mechanism. This is why in the next chapters we suggest another way to research the B_c production mechanism.

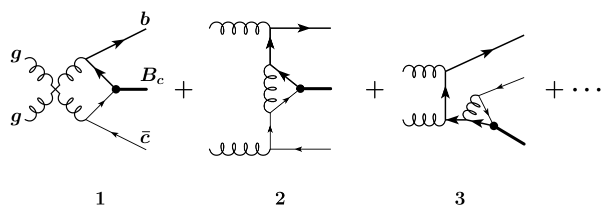
3. The cross section distribution on the invariant mass of D and B_c mesons

Within fragmentation approach the shape of the cross section distribution over the invariant mass of B_c and $\bar{c}$-quark is roughly determined by $\bar{b}$-quark virtuality (see the diagram (3) in Fig. 1). This why the distribution should be relatively narrow. Our analytical calculations confirm this supposition [14].

Here we face the problem how to transform the invariant mass of B_c (B_c^*) and $\bar{c}$-quark $M_{B_c+\bar{c}}$ to invariant mass of B_c (B_c^*) and $\bar{D}$-meson $M_{B_c+\bar{D}}$. Within the fragmentation mechanism it is naturally to assume that the $\bar{D}$ meson takes away the total momentum of c-quark, because the production of $\bar{c}$ quark is the last step of emission process. Such an assumption is not obvious for the recombination contribution. This is why two hadronization models of $\bar{c}$ quark have been chosen:

1. $\bar{D}$ meson takes away the total momentum of $\bar{c}$-quark: $D_{c\to D} = \delta(1-z)$;

2. $\bar{D}$ meson takes away part of $\bar{c}$-quark momentum according to Kartvelishvily-Petrov-Likhoded fragmentation function: $D_{c\to D} = z^{2.2}(1-z)$.



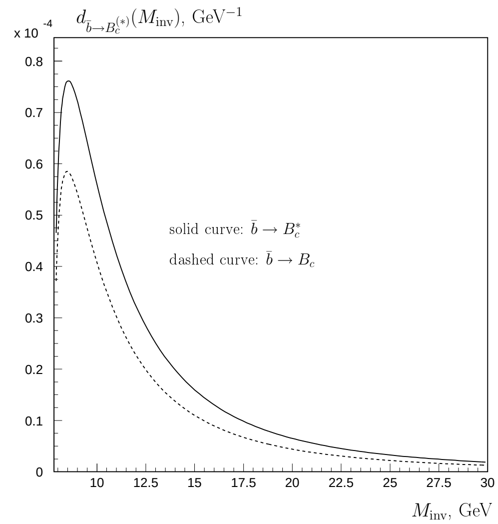


Figure 1: The leading order diagrams for the process $gg \to B_c + b + \bar{c}$.

Figure 2: The normalized cross section distributions over the invariant mass of B_c (B_c^*) and c-quark within fragmentation approach.

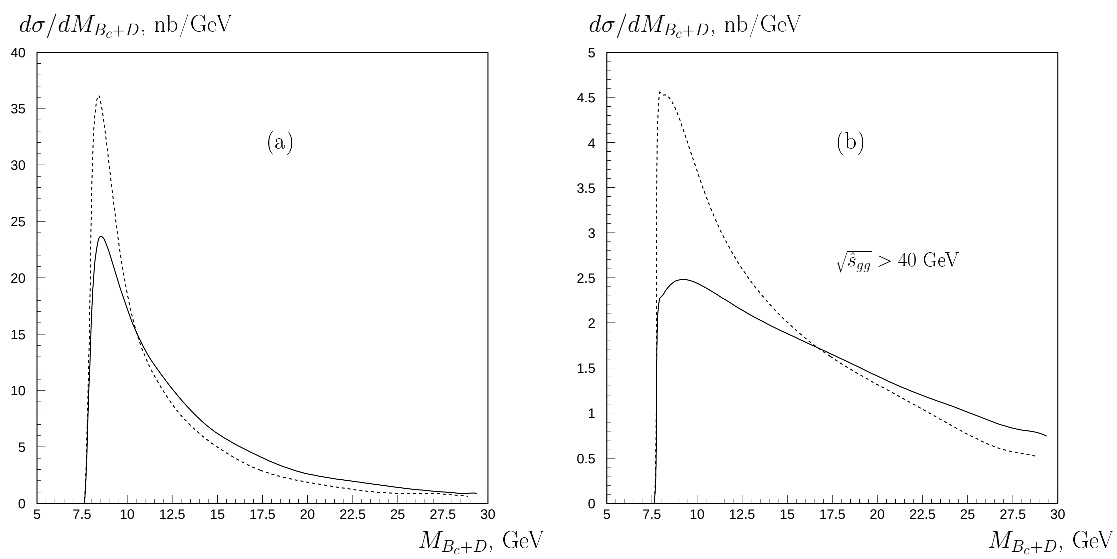


Figure 3: The cross section distributions over the invariant mass of B_c and $\bar{D}$ mesons calculated within pQCD for the process $pp \to B_c + X$ at $\sqrt{s} = 14$ TeV: without cuts (a) and for $\sqrt{\hat{s}} > 40$ GeV (b). Solid curves: $D_{c\to D} = \delta(1-z)$; dashed curves: $D_{c\to D} = z^{2.2}(1-z)$.

The cross section distributions over $M_{B_c+\bar{D}}$ are shown in Fig. 3 for the different kinematical regions. One can see that for the total phase space the cross section distribution looks like the obtained within the fragmentation approach, but the cut on interaction energy essentially transforms the distribution shape. It become essentially wider, whereas within the fragmentation approach it should remain the same. Thus one can conclude that the recombination contribution is dominant.

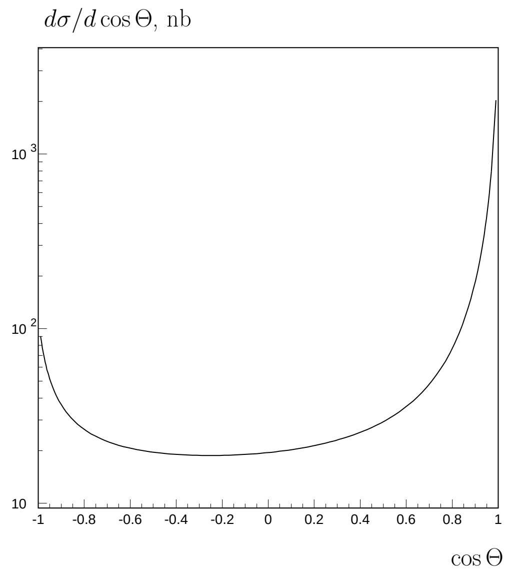


Figure 4: The cross section distribution over the cosine of angle between the directions of motion of B_c and $\bar{D}$ mesons predicted within pQCD for the process $pp \to B_c + X$ at $\sqrt{s} = 14$ TeV.

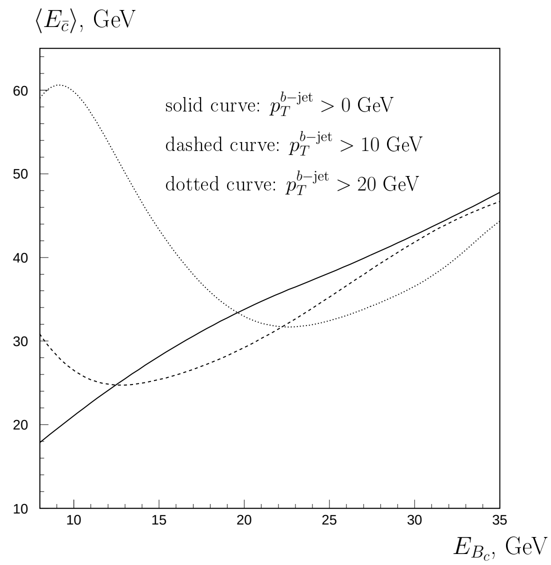


Figure 5: The dependencies of averaged $\bar{c}$ quark energy on B_c meson energy are represented for the different cuts on b-jet transverse momenta.

4. The angle correlations and the decay length ratio in the associative production of B_c and D mesons.

As it is shown in Fig. 4, the cross section distribution on cosine of the angle between the B_c meson and $\bar{D}$ meson has the sharp maximum at $\cos\theta \sim 1$. Moreover, about a half of B_c mesons is associated by the $\bar{D}$ meson moving in the close direction: $\theta \lesssim 26^o$. Therefore, $\bar{D}$ meson can be used to detect B_c meson.

In the Fig. 5 the dependencies of averaged $\bar{c}$ quark energy on B_c meson energy are represented for the different cuts on b-jet transverse momenta. It can be concluded from these plots that at any b-jet transverse momentum

$$\langle E_{\bar{c}} \rangle \gtrsim 1.2 E_{B_c}. \tag{4.1}$$

For $\bar{D}$ meson we obtain that

$$\langle E_{\bar{D}} \rangle \gtrsim 0.7 \div 1.2 E_{B_c} \tag{4.2}$$

for $D_{c\to D} = z^{2.2}(1-z)$ and $D_{c\to D} = \delta(1-z)$, correspondingly.

The decay lengths depend on particle energies and lifetimes as follows:

$$\langle l_{\bar{D}} \rangle \simeq \frac{\langle E_{\bar{D}} \rangle}{m_D} c\tau_D \qquad l_{B_c} \simeq \frac{E_{B_c}}{m_{B_c}} c\tau_D. \tag{4.3}$$

Taking into account that $\tau_D/\tau_{B_c} \simeq 2$ we obtain:

$$\frac{\langle l_{barD} \rangle}{l_{B_c}} \gtrsim 5. \tag{4.4}$$

This value should be compared with the fragmentation model prediction:

$$\frac{\langle l_{\bar{D}}^{\text{frag}} \rangle}{l_{B_c}^{\text{frag}}} \sim 1 \div 2. \tag{4.5}$$

5. Conclusions

The following conclusion can be drawn from the performed calculations:

1. The cross section distribution over the invariant mass of B_c and $\bar{D}$ meson depends essentially on kinematical cuts and can be used to research B_c production mechanism at LHC.
2. In many cases the B_c and $\bar{D}$ mesons move in close directions. It could be useful to detect B_c meson.
3. The energies of B_c and $\bar{D}$ mesons are comparable. The decay length of $\bar{D}$ meson by more than 5 times larger than the decay length of B_c meson. The experimental research of the ratio between B_c meson and $\bar{D}$ meson energies could shed light on B_c production mechanism.

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